Vacuum Polarization by Scalar Field of Bose-Einstein Condensates and Experimental Design with Laser Interferences

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In a five-dimensional gravitational theory (or 5D gravity), a scalar field is usually included to couple with the gravitational and electromagnetic fields, which are directly originated from or generated by the mass and electric charge of matter, respectively. Theoretical analyses have shown that the scalar field of 5D gravity can polarize the space (or vacuum) and shield gravity (or flatten spacetime), especially when the object that generates the fields is extremely compact, massive, and/or highly charged. Recently, the scalar field of 5D gravity has been directly connected to the Higgs field of 4D particle physics, so that it dramatically relates to the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with superconductors and/or superfluids. Therefore, the scalar field effect on the properties of light and the weight of objects may be detectable in a laboratory of low temperature physics. In this study, we first analyze the index of refraction of the space or vacuum that is polarized by scalar field. We then explore approaches of detection and design experiments to test the space polarization or the effect of scalar field on light as well as the equivalence or connection between the scalar field of 5D gravity and that of 4D particle physics.

1 Introduction

In contrast to the vector field of electromagnetism and the tensor field of gravitation, a scalar field is a field that has no direction. Up to now, many physical phenomena are explained with the physics of scalar fields such as the cosmic inflation [1-2], dark matter [3-4], dark energy [5-6], particle mass generation [7-9], particle creation [10], gravitational field shielding [11-12], space or vacuum polarization [13-15], and so on. In the particle physics, the Higgs field, which generates masses of particles such as leptons and bosons, is a scalar field associated with particles of spin zero. In the 5D gravity, the gravitational and electromagnetic fields are coupled with a scalar field. Theoretical analyses have shown that the scalar field of 5D gravity can polarize the space or vacuum [13-15] and shield the gravity or flatten the spacetime [11-12,16-17], especially when the object of the fields is extremely compact, massive, and/or highly charged.

The scalar field of the 5D gravity has a direct relation or connection to the Higgs scalar field of the 4D particle physics [18]. The Higgs boson or Higgs particle is an elementary particle initially theorized in 1964 [7-9] and tentatively discovered to exist by the Large Hadron Collider at CERN [19]. This tentative discovery confirmed the existence of the Higgs scalar field, which led to the Nobel Prize of physics in 2013 to be awarded to Peter W. Higgs and Francois Englert. The Higgs mechanism is a process for particles to gain masses from the interaction with the Higgs scalar field. It describes the superconductivity of vacuum according to the Ginzburg-Landau model of the Bose-Einstein condensates.

Therefore, the scalar field of the 5D gravity can be considered as a type of Higgs scalar field of 4D particle physics. The latter can be considered as a type of Ginzburg-Landau scalar field of the Bose-Einstein condensates [20-21]. Then, that the scalar field of the 5D gravity can shield the gravitational field (or flatten the spacetime) and polarize the space or vacuum must imply that the Ginzburg-Landau scalar field of superconductors and superfluids in the state of Bose-Einstein condensates can also shield the gravitational field (or flatten the spacetime) and polarize the space or vacuum.

In fact, the experiment conducted about two decades ago had indeed shown that a rotating type-II ceramic superconductor disk at low temperature could have a moderate (∼2 – 3%) shielding effect against the Earth gravitational field [22]. The experiment conducted later for a static testing with the shielding effect of ∼0.4% [23]. Recently, we have explained these measurements as the gravitational field shielding [12] by the Ginzburg-Landau scalar field of Bose–Einstein condensates associated with the type II ceramic superconductor disk according to the 5D fully covariant gravity developed by Zhang [11,15,24].

In this paper, we will focus on the vacuum polarization by scalar field and its testing. We will explore some possible approaches and further design viable experiment setups to test the space or vacuum polarization by the scalar field (*i.e.* the effect of scalar field on light). We will, at first, apply the fully covariant 5D gravity with a scalar field that was developed by Zhang [11,15] and references therein to formulate the index of refraction in the vacuum that is polarized by the scalar field of this 5D gravity. Then, we will employ the Ginzburg-Landau scalar field generated by the Bose-Einstein condensates of superconductors and superfluids to replace or add the scalar field of the 5D gravity. Finally, we will design an experiment setup of laser light interferences that may detect the vacuum polarization by the Ginzburg-Landau scalar field and thus test Zhang's theory of vacuum polarization by scalar field as well as Wesson's equivalence and connection between the scalar field of 5D gravity and the scalar field of 4D particle physics.

2 Index of refraction of the vacuum polarized by the scalar field

According to the 5D fully covariant gravity with a scalar field [15] and references therein, we can determine the index of refraction of the vacuum that is polarized by the scalar field as

$$n \equiv \sqrt{\epsilon_r} = \Phi^{3/2} \exp\left(\frac{\lambda - \nu}{4}\right). \tag{1}$$

Here, Φ is the scalar field and the functions, e^{λ} and e^{ν}, are the $rr-$ and $tt-$components of the 4D spacetime metric. Both the scalar field and the metric components are completely determined according to the exact field solution obtained by Zhang [15] and references therein without any unknown parameter.

For objects in labs and the Earth itself, the fields of 5D gravity are weak, so that we can approximately represent $\Phi \sim 1 + \delta\Phi$, $e^{\lambda} \sim 1$, and $e^{\nu} \sim 1$. Then, the index of refraction in the vacuum that is polarized by scalar fields reduces to

$$n = 1 + \frac{3}{2}\sum \delta\Phi = 1 + \frac{3}{2}\left(\delta\Phi_{5D} + \delta\Phi_{GL}\right). \tag{2}$$

Here, Σ refers to the summation of contributions from all kinds of scalar fields, including the scalar fields of the 5D gravity from the Earth and any other charged objects and the Ginzburg-Landau scalar fields of the 4D particle physics from the Bose-Einstein condensates associated with superconductors and superfluids.

According to Zhang's fully covariant 5D gravity [15] and references therein such as [11,24], the scalar field of a charged object with charge Q and mass M is given by,

$$\delta\Phi_{5D} = \frac{2GM(1+3\alpha^2)}{3\sqrt{1+\alpha^2 c^2}}\,\frac{1}{r}, \tag{3}$$

where

$$\alpha = \frac{Q}{2\sqrt{G}M} \tag{4}$$

is a constant in cgs units, G is the gravitational constant, c is the light speed in free space, and r is the radial distance from the object. Considering an object with mass of 600 kg and charge of 0.01 C, we have $\alpha \sim 10^5$ and $\delta\Phi_{5D} \sim 10^{-19}$ at 1 m radial distance. For Earth, we have $\alpha \sim 0$ and $\delta\Phi_{5D} \sim 5 \times 10^{-10}$ on the surface. Therefore, via Earth or a charged object in labs, the scalar field of the 5D gravity is negligibly weak, *i.e.* $\delta\Phi_{5D} \sim 0$, and the effect on the vacuum polarization may be extremely difficult to detect. A new study by Zhang [25] has theoretically shown that the space or vacuum polarization by the scalar field of 5D gravity generated by a highly charged object may be directly detected by the extremely accurate Laser Interferometer Gravitational-Wave Observatory (LIGO), which has recently detected first ever the gravitational waves from a binary black hole merger as claimed in [26].

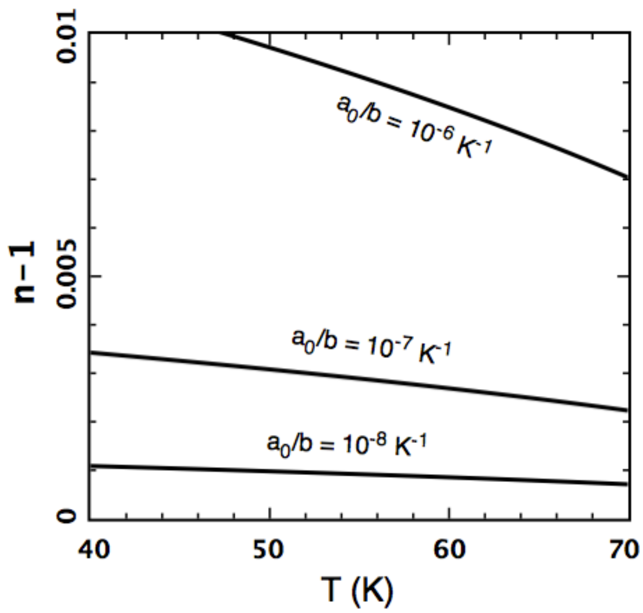

Fig. 1: The change for the index of refraction of the vacuum $(n-1)$ versus the temperature of the superconductor (T). The vacuum is polarized by the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with a type II superconductor whose transition temperature is $T_c = 92$ K. Three lines correspond to three cases for the ratio of the two phenomenological constants to be $a_0/b = 10^{-8}, 10^{-7}, 10^{-6}$ K, respectively.

The Ginzburg-Landau scalar field of Bose-Einstein condensates associated with superconductors and superfluids can be expressed as [20-21,27],

$$\delta\Phi_{GL} = \sqrt{-\frac{a_0}{b}\left(T - T_c\right)}, \tag{5}$$

where a_0 and b are the phenomenological constants, T is the temperature, and T_c is the transition temperature. A type II superconductor, if its Ginzburg-Landau scalar field can produce a few percent (*e.g.* 2 – 3%) weight loss for a sample as experimentally shown by [22-23], can also polarize the vacuum by increasing the index of refraction about a detectable percentage. For a quantitative study, we plot in Fig. 1 the index of refraction in the vacuum that is polarized by the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with a type II superconductor as a function of the temperature of the superconductor. In this plot, we have chosen the values $T_c = 92$ K and $a_0/b = 10^{-8}, 10^{-7}, 10^{-6}$ K^{-1} as done in [12].

It is seen that due to the polarization the index of refraction of the vacuum can be increased by $\sim 0.1 - 1\%$ for the ratio of the phenomenological constants to be in a range of $a_0/b = 10^{-8} - 10^{-6}$ K^{-1}, which could lead to ~2 – 3% weight loss for a sample as shown in [12]. This significant increase of the index of refraction should be detectable in an optical experiment. In the following section, we design an experiment to test this scalar field effect on light or space polarization here predicted according to Zhang's 5D fully covariant gravity and Wesson's scalar field equivalence or connection between the 5D gravity and the 4D particle physics. Superfluids, though the transition temperature is lower but if the ratio of phenomenological constants is higher, can also generate a significant scalar field to polarize the vacuum.

3 Experimental design and prediction

A laser light beam that has passed through a spatial filter can be separated into two beams by a beam separator. These two laser light beams once reflected by two mirrors into the same region will interfere. If the difference of their optical distances travelled by the two beams is a factor of a whole number of the light wavelength, the interference is constructive otherwise the interference is destructive. A bright and dark pattern of interference is formed in the interference region. Now, if one of the two laser light beams passes through the space or vacuum that is polarized by scalar fields, then the interference pattern will be changed. This is because the space polarization lengthens the optical length of the path of the light beam.

The interference pattern will change from bright to dark or dark to bright, if the extra optical distance traveled for the beam that has passed through the space or vacuum polarized by scalar fields is given by

$$(n-1)\,D = \left(m + \frac{1}{2}\right)\lambda\,, \qquad (6)$$

where n is the index of refraction of the space or vacuum that is polarized by the scalar field and its relation to the scalar field is given by (1) or (2); D is the dimension of the object that produces the scalar field; $m + 1$ is the number of shifting the interference pattern from bright to dark (only one shift from bright to dark if $m = 0$); and λ is the wavelength of the laser light. The interference pattern does not change, if the extra optical distance is a whole number of the light wavelength, *i.e.* $(n-1)\,D = m\lambda$.

To polarize the space or vacuum that one of the two laser light beams travels through, we can place or put an electrically charged object, a type II ceramic superconductor disk, or a superfluid torus near the path of the beam (Fig. 2). Of course, we can put all of them together to enhance the total scalar field. Two superconductor disks can also double the effect. In these cases, the parameter D in (6) can be roughly estimated as the diameter of the charged object, superconductor disk, or superfluid torus.

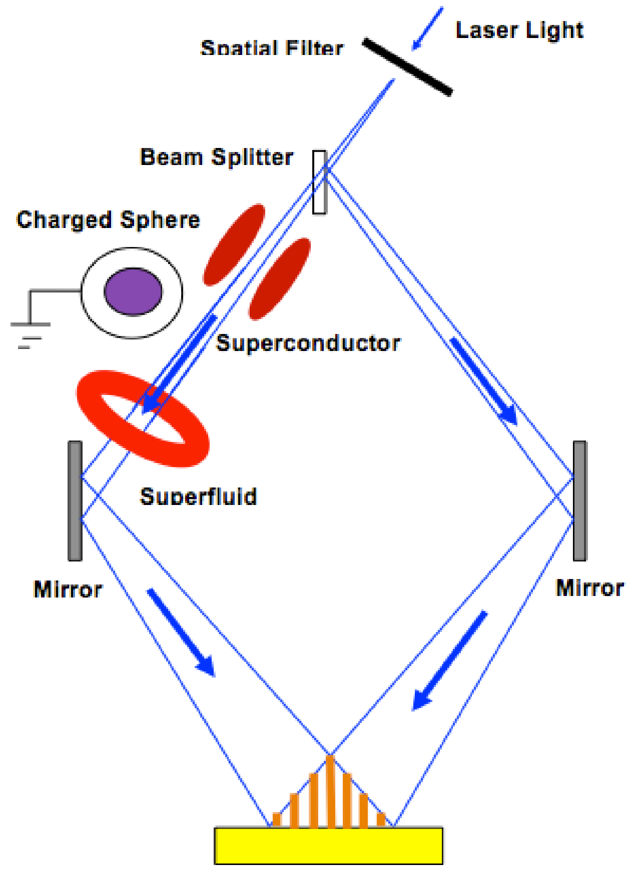

Fig. 2: A schematic diagram for the experimental setup to test the vacuum polarization by scalar field. A laser light that passes a spatial filter can be separated into two beams by a beam separator. The two beams once reflected by two mirrors into the same region will interfere and produce a bright-dark interference pattern. When the space or vacuum for the path of one beam is polarized by the scalar field generated by charged objects, superconductor disks, and/or superfluid toruses, the interference pattern will be varied or shifted. Therefore, the detection of any variation or shifting of the interference pattern will test the theory for the vacuum polarization by scalar field and the equivalence or connection for the scalar fields of 5D gravity and 4D particle physics.

As pointed out above, since it is not enough compact, massive, and/or highly charged, an object in labs cannot generate a significant scalar field to polarize the space or vacuum up to a detectable level, but except for LIGO [25-26]. The extra optical distance that a charged object can produce is $(n-1)\,D = 3/2\,\delta\Phi_{5D} D \sim 10^{-19}$, which is too small in comparison with the wavelength of light. Therefore, a charged object cannot lead to a measurable shifting of the interference pattern. The scalar field of 5D gravity due to the Earth can neither vary the interference pattern, because it evenly affects both the beams of laser light.

To see how significant for a type II ceramic supercon-

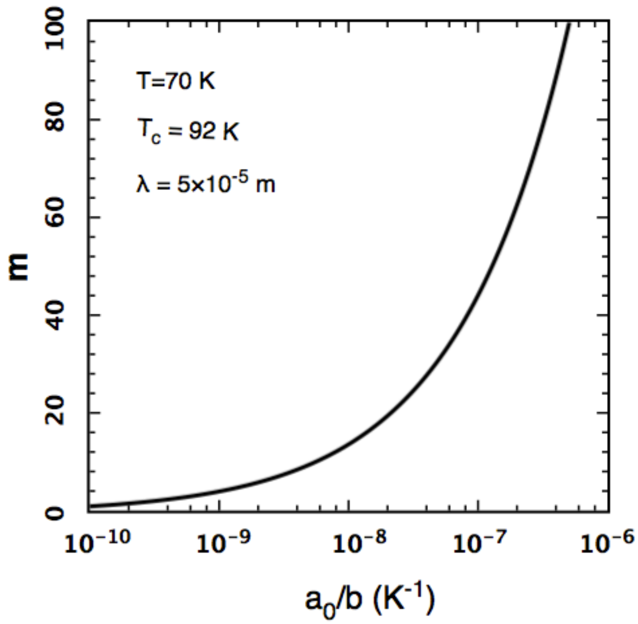

Fig. 3: The number of shifting the interference pattern from bright to dark, m, versus the ratio of the phenomenological constants, a_0/b. The temperature and transition temperature of the conductor are chosen as = 70 K and T_c = 92 K, respectvely.

ductor disk to vary the interference pattern, we plot in Fig. 3 the number of shift, m, as a function of the ratio of the phenomenological constants, a_0/b, according to (6) with (2) and (5). Here, we have chosen $D = 0.11$ m, $T_c = 92$ K, and $T = 70$ K according to the previous laboratory experiment [22] and analytical study [12]. The wavelength is chosen as a blue light with $\lambda \sim 5 \times 10^{-5}$ m. It is seen that the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with a type II ceramic superconductor disk can lead to a significant shifting of the interference pattern. This varying of interference pattern is detectable only needing the ratio of the phenomenological constants to be greater than about 10^{-10} K^{-1}. Therefore, the effect of scalar field on light (or the space polarization) should be much more easily detected than the effect of scalar field on weight (or the gravitational field shielding).

4 Discussions and conclusions

We have investigated the vacuum polarization by the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with superconductors and superfluids. First, we have formulated the index of refraction of the vacuum that is polarized by the scalar field according to Zhang's 5D fully covariant gravity and Wesson's equivalence or connection of scalar fields between 5D gravity and 4D particle physics. Then, we have designed an experimental setup with laser light interferences to detect the effect of scalar field on light and hence the vacuum polarization by the Ginzburg-Landau scalar field. Via this study, we have seen that the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with a type II ceramic superconductor disk can cause a significant and thus detectable shifting of the laser light interference pattern. The ratio of the phenomenological constants can be much smaller than that for a detectable weight loss of a sample. Therefore, we have provided a possible approach and experimental setup for detecting the effect of scalar field on light in labs. In future, we will implement the design to conduct the experiment and perform the testing.

Acknowledgements

The author (B.J.Z.) is grateful for the support of educations in physics and engineering from Vanderbilt University, Georgia State University, and University of Alabama in Huntsville. He is especially appreciating very much for Dr. A. Kozhanov from Georgia State University and Dr. P. Reardon from University of Alabama in Huntsville for their great supervisions on his graduate study for Masters of Physics (2015) and Masters of Electrical Engineering in the concentration of optics (2017). He also thanks Dr. P. Guggilla, Dr. M. Edwards, and Dr. M. Aggarwal from Alabama A & M University for their support. This work was partially supported by the NSF/REU programs (Grant #: PHY-1263253, PHY-1559870) at Alabama A & M University.

Received on September 16, 2017

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